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RESEARCH ARTICLE

ANALYTICAL MODELLING FOR CONFINEMENT OF HIGH STRENGTH CONCRETE COLUMNS WITH GLASS FIBRE REINFORCED POLYMER WRAPPING

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ABSTRACT

Fibre reinforced polymer confined columns have been developed for new construction rehabilitation of concrete structures such as piers or piles in civil engineering field. The design oriented confinement model predominant in designing FRP confined concrete columns. The design model is directly based on in interpretation of experimental result. In this study one model is presented for reinforced concrete columns externally reinforced with fibre reinforced polymer wraps using finite element method adopted by ANSYS software. The finite element model was developed using for concrete and the three dimensional layer elements for the fibre reinforced polymer composites. The result obtained from those finite element analysis results were compared on the experimental data for respective concrete column with different conditions from researcher. From the analysis load deflection, stress strain relationship, performance characteristics of GFRP wrapped column were also to be studied. The prediction of ANSYS model agreed with the experimental results.

INTRODUCTION

Reinforced Concrete columns have an important function in the structural concept of many structures. Often, these columns are vulnerable to exceptional loads (such as impact, explosion, or seismic loads), confinement of concrete is an efficient technique to increase the load-carrying capacity and ductility of concrete columns primarily subjected to compression. By providing lateral confining pressure, the concrete is subjected to a tri-axial state of stress, so that the compressive strength and deformability increase. The lateral confining action is mostly induced in a passive way by restraining the lateral expansion of the concrete through closely spaced stirrup or hoop reinforcement. Since the introduction of FRP as externally bonded reinforcement, confinement by means of FRP wrapping has been of considerable interest for upgrading columns, piers, and chimneys. Reinforced concrete structures are commonly designed to satisfy both serviceability and safety criteria. To ensure the serviceability requirement, prediction of cracking and estimation of deflection under service loads need to be considered. To meet the safety or strength requirement, an accurate estimation of the ultimate load is essential but it is also desirable to predict load-deformation characteristics of the structure.

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Because of the complexities associated with the development of rational analytical procedures for reinforced concrete, many design methods still rely on the empirical approach, using the test results from a large number of experiments. Nowadays, with the availability of inexpensive and high-performance computers and well-developed FEA software, FEA is now a powerful and general analytical tool to model the behavior of structural concrete. Through FEA, important parameters like stress-strain relationships, cracking model, etc., those have significant influence on the structural concrete behavior can be conveniently and systematically investigated.

However, the need for some form of experimental research still continues to provide a firm basis for design equations. Experimental data also supply the much needed information, e.g. material property, to validate the mathematical models for FEA. On the other hand, reliable FE models can considerably cut down the number of experiments required, hence reducing both time and cost of solving a given problem (Amir Mirmiran *et al.*, 2000). The authors (Desayi and Krishnan, 1967; Hadi, 2007) were studied the behaviour of high strength concrete short column confined by spiral and square ties. The test variables Included volumetric ratio, spacing of Yield strength of transverse reinforcement, longitudinal reinforcement ratio, lateral steel configuration. Authors presented effect of variables on uniaxial behaviour of high strength column.

Authors discussed the results indicate that more confinement is required in columns high strength concrete than in columns of low strength concrete to achieve the desired post-peak deformability and behaviour of high strength columns is characterized by the sudden spalling of concrete cover leading to a loss of axial capacity. The authors (Hadi, 2007; Hadi, 2003; Yong *et al.,* 1998) conducted an investigation on behaviour of high strength concrete columns with FRP confinement. The specimens were confined using carbon, glass and Kevlar fibre reinforced polymer of varying thicknesses and subjected to concentric as well as eccentric loading. The authors concluded that all columns failed in a brittle manner. The failure of unconfined columns was highly explosive. Under concentric loading conditions, confinement using Kevlar FRP resulted in some increase of deflection and ductility over the unconfined specimens. Carbon fibre wrapped specimens with single layer failed explosively, while those with three layers seemed to appear integral without any damage to the wrap even after failure of the column. Under eccentric loading, carbon FRP confined columns failed explosively, while kevlar and glass FRP confined specimens showed adequate warning in the form of white patches on FRP surface at the time of initiation of failure.

The author (Nagaradjane, 2007) presented on a sensitivity study and design procedure for FRP wrapped RC circular columns, subjected to an axial load and equal end moments. The parameters used in the study include the unconfined concrete strength, steel ratio, thickness of FRP wraps and the section diameter. Interaction equations were also developed in this work to provide a simplified and practical tool for engineers to evaluate the ultimate strength of the FRP wrapped columns. The author concluded that FRP wraps significantly increase the ultimate strength of RC columns. The rate of increase in strength increases proportionally to the increase in FRP layer thickness.

Experimental Investigation

Experimental investigation was carried out on seven columns having similar slenderness ratio, different wrap thickness and wrap materials. The specimen consisted of column having 150mm diameter and 900 mm height. All the specimens were tested in a loading frame of 2000KN capacity till failure.

MATERIALS AND METHOD

High strength concrete, ribbed tor steel bars for longitudinal reinforcement, mild steel for lateral ties and Glass fibre reinforced Polymer (GFRP) were used.

Concrete

The concrete mix ratio for design strength was 1:1.35:2.14:0.29:0.8(1 part of cement,1.35 parts of fine aggregate,2.14 parts of coarse aggregate 0.29 parts of water and 0.8% parts super plasticizer).

Steel

High yield strength Deformed (HYSD) having yield strength of 415 MPa were used for longitudinal reinforcement.Fe250 grade mild steel bars were used for lateral ties.

Glass fibres

The three types of Glass fibre was used for the investigation. The glass fibre fabrics were applied on the surface of the column using iso-phthalic resin to form the wrap material.

Specimen Details

The specimen consisted of reinforced concrete columns having 150mm diameter, reinforced with six rods, 8mm diameter ribbed tor steel bars and 6mm diameter steel ties at spacing of 120mm c/c. The details of specimens are presented in Table 1.

Table 1. Specimen Details

S.No	Specimen designation	Diameter(mm)	Height(mm)	Type of GFRP	Thickness of GFRP(mm)
1	R0	150	900	-	-
2	UDC3	150	900	UDC	3
3	UDC5	150	900	UDC	5
4	CSM3	150	900	CSM	3
5	CSM5	150	900	CSM	5
6	WR3	150	900	WR	3
7	WR5	150	900	WR	5

However, in terms of the effect of the steel ratio, it has been found that the rate of increase in strength is lower for higher levels of steel ratio. The proposed interaction equation has been verified for a simply supported FRP wrapped column subjected to equal end moments and found that these equations are reliable for predicting the ultimate strength. The study also looks into the strength modeling of FRP confined concrete that is the effective circumferential FRP failure strain and the effect of increasing confining action. Different models are reviewed and were used to predict the ultimate strength. The experimental and analytical results are compared with those result obtained by the previously published models.

The specimens were classified based on their slenderness ratio. The nominal slenderness ratio S24 was adopted for 900 mm column. The nominal slenderness ratio was calculated using expression 1.

$$\lambda_n = l_{eff}/r_g \qquad \text{……………………………………………} \quad (1)$$

Where, λ_n is nominal slenderness ratio, l_{eff} is the effective length of the column, r_g is radius of gyration

Modelling

The current study presents results from the finite element analysis of seven full scale columns.

The finite element model used a smeared cracking approach and three dimensional layered elements to model FRP composite comparison between finite element results and those from the experimental columns are shown. The ANSYS finite element program (ANSYS 10.0) operating on a UNIX system was used in this study to stimulate the behaviour of seven experimental columns. In general conclusions and methods would be very similar using other nonlinear FEA programs each program; however has its own nomenclature and specialized elements and analysis procedure that need properly.

Element Types

Reinforced Concrete

An eight-node solid element, Solid65, was used to model the concrete. The solid element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The geometry and node locations for this element type are shown in Fig.3.1.

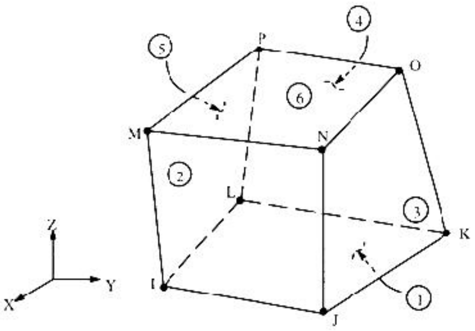

Fig. 3.1. solid65 element geometry

A Link8 element was used to model the steel reinforcement. Two nodes are required for this element. Each node has three degrees of freedom, – translations in the nodal x, y, and z directions. The element is also capable of plastic deformation. The geometry and node locations for this element type are shown in Fig.3.2

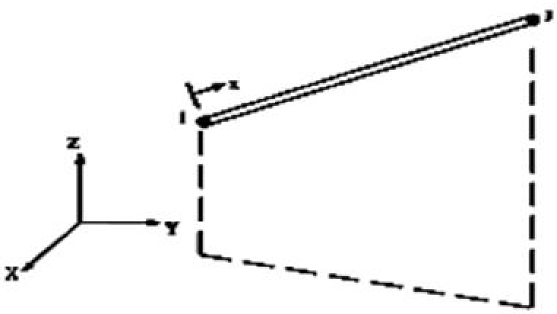

Fig. 3.2. Link8 Element Geometry

FRP Composites

A layered solid element, Solid46, was used to model the FRP composites. The element allows for up to 100 different material layers with different orientations and orthotropic material properties in each layer.

The element has three degrees of freedom at each node and translations in the nodal x, y, and z directions. The geometry, node locations, and the coordinate system are shown in Fig.3.3.

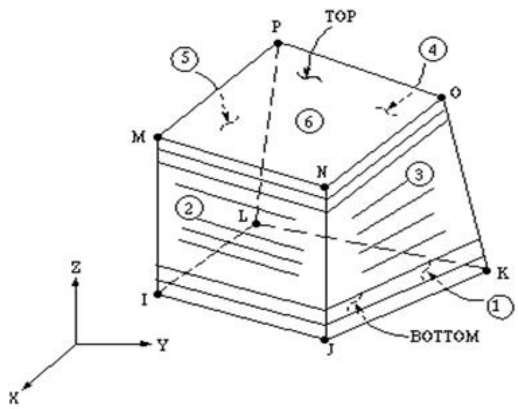

Fig. 3.3. Solid45 Element Geometry

Material Properties

Concrete

Concrete is a quasi-brittle material and has different behavior in compression and tension. The tensile strength of concrete is typically 8-15% of the compressive strength (Shah, et al. 1995). For concrete, ANSYS requires input data for material properties as follows:

Elastic modulus (E_c).Ultimate uniaxial compressive strength (f'_c).Ultimate uniaxial tensile strength (modulus of rupture, f_r).Poisson's ratio (ν). Shear transfer coefficient (β_t).Compressive uniaxial stress-strain relationship for concrete. The ultimate concrete compressive and tensile strengths for each column model were calculated by Equations 3.1, and 3.2, respectively (IS456-2000).

Modulus of Elasticity [*Ec*]

$$Ec = 5000 \sqrt{fck} \quad N/mm^2 \quad \text{………………..} (3.1)$$

Where *fck* = Compressive strength (N/mm^2)

Poisons' ratio [υ] υ =0.2 Modulus of Rupture [*fr*], (Ultimate tensile strength)

$$f_r = 0.7\sqrt{fck} \quad N/mm^2 \quad \text{………………….} (3.2)$$

The shear transfer coefficient, β_t, represents conditions of the crack face. The value of β_t ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer).A number of preliminary analyses were attempted in this study with various values for the shear transfer coefficient within this range, but convergence problems were encountered at low loads with β_t less than 0.2. Therefore, the shear transfer coefficient used in this study was equal to 0.2.

The ANSYS program requires the uniaxial stress-strain relationship for concrete in compression. Numerical expressions (Desayi and Krishnan 1964), Equations 3.3 and 3.4 were used along with Equation 3.5 (Gere and Timoshenko 1997) to construct the uniaxial compressive stress-strain curve for concrete in this study.

$$f = \frac{Ec\ \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \quad \text{.......................... (3.3)}$$

$$\varepsilon_0 = \frac{2f'c}{Ec} \quad \text{.. (3.4)}$$

$$Ec = \frac{f}{\varepsilon} \quad \text{.. (3.5)}$$

Where: f = stress at any strain ε, psi

ε = strain at stress f, psi
ε_0 = strain at the ultimate compressive strength f_c'

Steel Reinforcement

The steel for the finite element models was assumed to be an elastic-perfectly plastic material and identical in tension and compression. Poisson's ratio of 0.3 was used for the steel reinforcement in this study.

Fibre Reinforced Polymer Composites

The FRP composites are anisotropic materials; that is, their properties are not the same in all directions. The xyz coordinate axes are referred to as the principal material coordinates where the x direction is the same as the fiber direction, and the y and z directions are perpendicular to the x direction. The schematic of FRP composite is shown in Fig.3.4. In this study, the specially orthotropic material is also transversely isotropic, where the properties of the FRP composites are nearly the same in any direction perpendicular to the fibers.

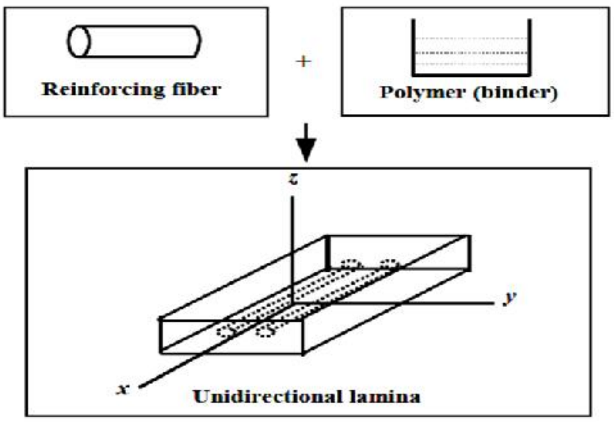

Fig. 3.4. Schematic of FRP Composite

Thus, the properties in the y direction are the same as those in the z direction. The properties of isotropic materials, such as elastic modulus and Poisson's ratio, are identical in all directions; therefore no subscripts are required. This is not the case with specially orthotropic materials. Subscripts are needed to define properties in the various directions. For example, $E_x \neq E_y$ and $\nu_{xy} \neq \nu_{yx}$. E_x is the elastic modulus in the fiber direction, and E_y is the elastic modulus in the y direction perpendicular to the fiber direction. Therefore, the orthotropic material data are supplied in the ν_{xy} or major Poisson's ratio format for the ANSYS program. The material properties of the FRP composites are calculated using micro mechanics approach. The equations (3.6 & 3.7) used for the analysis are given below:

$$E_X = E f V f + E_m V_m \quad \text{.. (3. 6)}$$

Where

$E f$ = Modulus of elasticity of the Fiber,
Em = Modulus of elasticity of the Matrix

$$\upsilon_{xy} = V_f \upsilon_f' + V_m\, \upsilon_m \quad \text{...................................... (3.7)}$$

Where υf = Poisson's ratio of fiber, υm = Poisson's ratio of matrix

Finite Element Discretization

As an initial step, the model is divided into a number of small elements, and after loading, stress and strain are calculated at integration points of these small elements. A convergence of results is obtained when an adequate number of elements are used in a model. This is practically achieved when an increase in the mesh density has a negligible effect on the results (Adams and Ashkenazi 1998).

Modeling and Meshing

A cylindrical coordinate system was created at the active working plane. A hollow cylinder was generated with the given thickness, diameter and height dimensions. A solid cylinder was also generated with the considered specifications. In this model, the hollow cylinder resembles the FRP composite and the solid cylinder represents the concrete. The two volumes were glued together, assuming a perfect bonding between the composite and the concrete. For the validation of the model, the dimensions used were the dimensions of the coupons and specimen used in the experiments. For the test database, the dimensions of the cylinder were the standard diameter 150 mm and height 900 mm. The generated model was meshed using mapped mesh which helps in controlling the number of elements. The fewer the number of elements, the coarse, the mesh is Refinement of the mesh increases the accuracy of the simulation also increasing the analysis time. The mesh size would vary with the dimension of the model. Element attributes were assigned to the respective elements. The hollow cylinder was meshed with SOLID46 and the solid cylinder with SOLD65 elements. The coordinate axes of all the elements of hollow cylinder are oriented to the cylindrical coordinate system.

Fig. 3.5. Modeling of Control Specimen

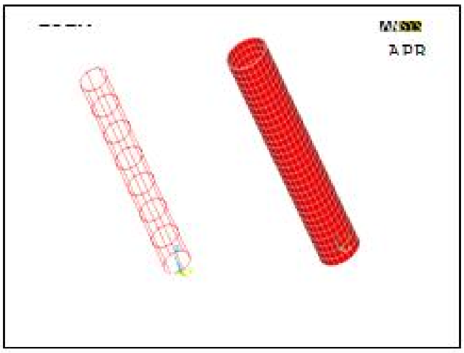

Fig. 3.6. Reinforcements, Stirrups and FRP Modeling for Strengthened Specimen

Fig. 3.5 shows the finite element model of the FRP confined concrete. Therefore, which was equivalent to 2320 elements in the full-column model, was selected for the Control column model and used as the basis of the other three FRP-strengthened column models as well.

Boundary Conditions and Loading

In the model, the Z-axis of the coordinate system coincides with the axis of the column. The X and Y axis represent the radial and hoop directions of the column respectively. The boundary conditions are: 1) one end of the surface was fixed i.e. all the six degrees of freedom on that surface were constrained. 2) An axial compressive pressure load was applied on the other surface. The axial pressure load was increased gradually until the FRP fails. This type of loading condition and boundary constraints are similar to cylinders under uni-axial compression test.

Fig. 3.7 demonstrates the loading and boundary conditions for an FRP jacketed concrete column.

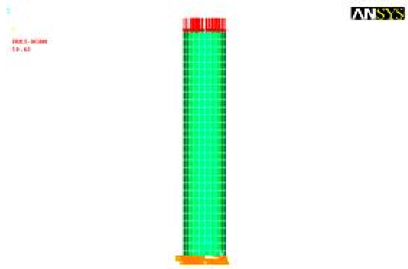

Fig. 3.7. Loading and Boundary Conditions For an FRP Wrapped Concrete Column

To apply the axial load on the top of the column specimen, an axial pressure was implemented over the entire top surface of the column model. Load step option may be used when the incremental loading is considered. ANSYS employs the "Newton-Raphson" approach to solve nonlinear problems. In this approach, the load is subdivided into a series of load increments problems. In this approach, the load is subdivided into a series of load increments.

The load increments can be applied over several load steps. This follows an iterative procedure until the problem converges. A number of convergence enhancement features are allowed in ANSYS like automatic load stepping, bisection etc can be activated to help the problem to converge. ANSYS to determine the number of load steps required for an accurate solution. Sub steps are defined to apply the loads gradually. The number of sub steps used for the simulation was 100, which sets the initial sub step to 1/100th of the total load. Providing all the necessary input, the simulation was performed.

Formation of target parameters

Output values were considered as the target parameters. These values were taken from the experimental result. The target parameters are ultimate load, axial deflection, lateral deflection, axial strain and lateral strain.

Training data

Training has been taken from the experimental result of the earlier studies. Analysis has been carried out for these data. Experimental results were shown in Table 3.1.

Table 3.1. Training Model-1- Experimental Results

Specimen Designation	Ultimate Load (KN)	Ultimate Axial Deflection(mm)	Ultimate lateral Deflection (mm)	Ultimate Axial strain με	Ultimate Lateral strain με
R0	1000	3.29	0.38	3655	2560
UDC3	1275	4.86	0.57	5400	3840
UDC5	1330	5.02	0.61	5577	4110
CSM3	1050	3.56	0.43	3955	2900
CSM5	1175	3.89	0.45	4322	3010
WR3	1120	4.16	0.45	4622	3060
WR5	1185	4.32	0.55	4800	3730

RESULTS AND DISCUSSION

Stress – Strain Behaviour

The ANSYS finite element model has been created, trained and validated with the result collected from the literature. ANSYS results and actual values were compared and the percentages of error were also predicted. Failure load was taken when the maximum failure strain is to be arrived .the maximum failure strain was taken in the previous literature for applied grade of concrete. The axial stress distributions of column specimens R0, UDC, WR, and CSM, obtained from the ANSYS solution. The axial stress-strain curves obtained from the ANSYS solution are confirmed by the training model results. From the comparisons for stress and strain curve of control specimen shown in Fig. 4.1. It shows that the predictions are in close agreement with the experimental curves.

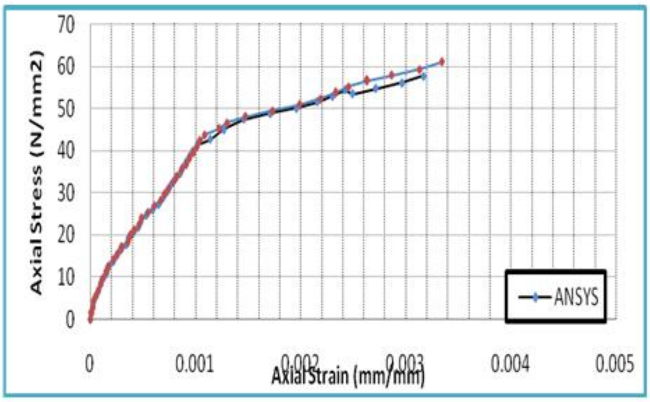

Fig. 4.1. Stress-Strain Plot for Control Column

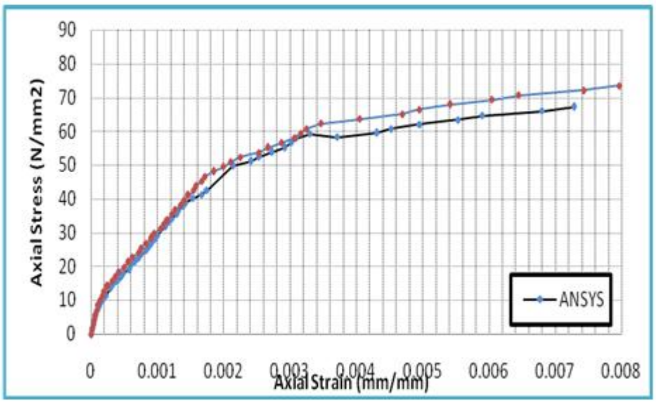

Fig. 4.2. Stress-Strain Plot for Wrapped Column

The linear stress-strain curves obtained from the ANSYS solution are confirmed by the training model results for FRP strengthening columns. From the comparisons for stress and strain curve of wrapped specimen shown in Fig. 4.2. It shows that the predictions are in close agreement with the experimental curves. Compare the seven finite element models figures show that the stiffness of the column before and after applying FRP strengthening is approximately the same in the linear range. The accuracy of the proposed procedure is also confirmed by the close values of maximum stress, strain at the maximum stress as well as strain when the stress drops to 70-80 percent of the maximum stress obtained from the FEM analysis and the experimental test.

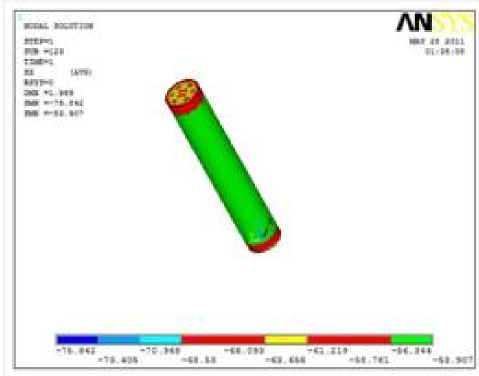

Fig. 4.3. Contour Plot of Stress of Control Specimen at Maximum Load

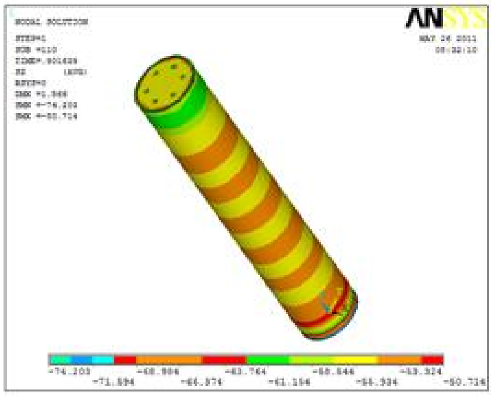

Fig. 4.4. Contour Plot of Linear Strain of Wrapped Column

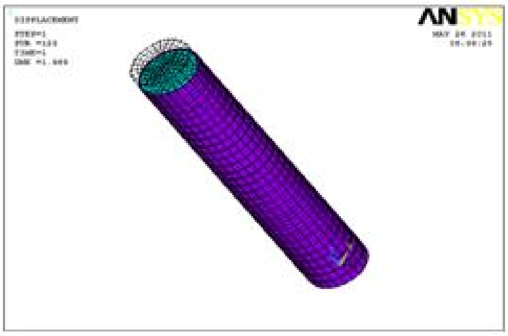

Fig. 4.5. Deformed Shapes of FRP Wrapped Column

The contour plot of stress for control specimen at maximum load was shown in Fig. 4.3. The contour plot of linear strain of wrapped specimen at maximum load was shown in Fig. 4.4. The contour plot of deformed shape of wrapped specimen was shown in Fig. 4.5. Ductility values for the columns were calculated based on deflection and energy absorption .the deflection a ductility values were calculated as the ratio between the deflection at ultimate point and the deflection at yield point. The energy ductility were calculated as the ratio of the cumulative energy absorption at ultimate point to the cumulative energy absorption at yield point

The deflection ductility (Δ_d) may be represented by

$$\Delta_d = \frac{\delta u}{\delta y} \qquad \text{.................................... (4.1)}$$

The energy ductility (Δ_e) may be represented by

$$\Delta e = \frac{\sum_{i=1}^{Nu-1} \frac{(\sigma_i + \sigma_{i+1})}{2} (\in_{i+1} - \in_{i+1})}{\sum_{i=1}^{Ny-1} \frac{(\sigma_i + \sigma_{i+1})}{2} (\in_{i+1} - \in_{i})} \quad \text{......... (4.2)}$$

Where, the is the deflection ductility, (Δ_e) is the energy ductility, δ_y is the deflection at yield point, δ_u is the deflection at ultimate point, N_u is the reading number at ultimate point N_y is the reading number at yield point, σ_i is the stress at i^{eth} point, ϵ_i is strain at i^{eth} point, dϵ is a small interval in the strain axis. Energy absorption signifies the total work done to make the specimen fail. The total energy absorption was calculated by the summation of the product of the load and deflection values over the bounds of the load deflection curve, the total area under the load deflection curve represent the energy absorption of the column loaded up to failure point. The total energy absorption may be calculated using equation 4.3 for experimental and analytical load deflection curves respectively

$$\eta_u = \sum_{N-1}^{N-1} \frac{(w_i + w_{i+1})}{2} (\delta_{i+1} - \delta_i) \quad \text{.................. (4.3)}$$

Where ηu is the total energy absorption, w is the load, δ is the deflection, δ_u is the ultimate deflection value and N is the total number of points in the experimental load deflection curve. The strain data from the finite element analysis and the experimental data for the FRP wrapped column have similar trends. Similar plot of strains in the FRP confined concrete column has lower strains than the experiment results, because of cracking load from the finite analysis also smaller in order comparing actual results. The finite element model for the compression member then has lower strains than the experimental results at whatever ultimate load comes from the ANSYS model. In case of S24CSM3 column the strain also reduced in order comparing training model results. This shows 24% reduction in strain comparing actual result. In the case load deflection plot, the control column, other wrapped column from both the experimental and the finite element analysis are reasonable good agreements. Finite element model is stiffer than actual columns in the linear range by approximately 6.8% and 10% respectively.

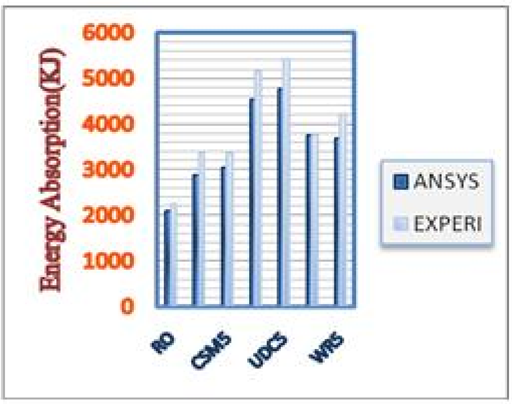

Fig. 4.6. Energy Absorption VS FRP Wrapped Columns

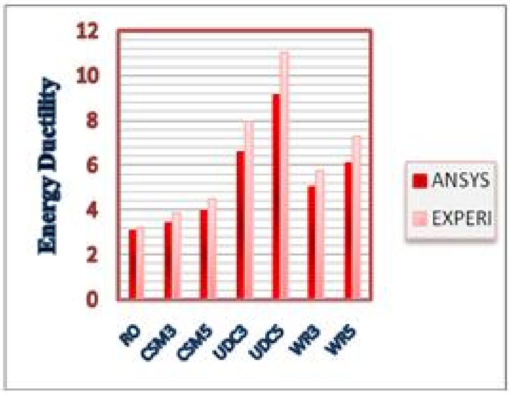

Fig. 4.7. Energy Ductility VS FRP Wrapped Columns

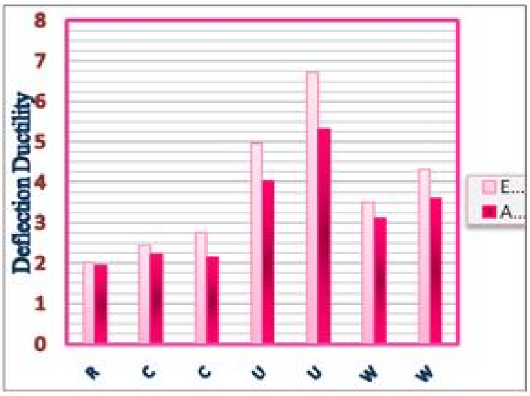

Fig. 4.8. Deflection Ductility VS FRP Wrapped Columns

In this case, in control column the load-deflection plot from the finite element analysis model is stiffer than that from the experimental results by approximately 8.8% the first failure load for the finite element analysis is 1000kN which is higher than the load of 900kN from the experimental results by 2%. In the case of control column large strains occur for the finite element model, whereas at a load of 825KN to 900KN similar behaviour takes place for the actual column. These loads are close to the yielding loads of the steel. For applied loads from 600 KN to maximum load, the load-strain plots from the finite element model and the experimental results do not correlate well. That may concluded experimental column exhibits nonlinear behaviour. The increases in failure strain values of conventional and GFRP wrapped columns by 7.83% and 20 to 24% respectively when comparing finite element model values to experimental values. Figs. 4.6, 4.7 and 4.8 shows the energy absorption, energy ductility and deflection ductility compared to experimental and analytical values respectively.

Conclusions

Based on Experimental results and those obtained through finite element analysis ANSYS based modeling.

- Values of strain at the maximum stress as well as strain drops 20% to 25% .The maximum stress obtained 75to 80 percent from the FEM analysis compared to experimental test values.

- Columns wrapped with unidirectional cloth glass reinforced polymer showed higher stress and higher ultimate strains result when compared to those wrapped with other type of FRP.
- Based on analytical modelling for FRP wrapped column, Energy ductility increased in the range of 10% to 31% for 5 mm thick wrapped column compared to 3mm thick wrapped columns.
- Based on analytical modelling for FRP wrapped column, Deflection ductility increased in the range of 4.7 % to 23% for 5 mm thick wrapped column compared to 3mm thick wrapped columns.
- The finite element model (FEM) has had the capability of ultimate stress and axial displacement prediction with an acceptable margin of errors. It offers very good correlation between the nonlinear results of the axially loaded columns and the experimental outcomes.

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